Teravolt Astrophysics—The Milagro Gamma-Ray Observatory

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Milagro is a new type of astronomical telescope. Like conventional telescopes, Milagro is sensitive to light, but the similarities end there. Whereas "normal" astronomical telescopes view the universe in visible light, Milagro "sees" the universe at very high energies. The "light" that Milagro sees is about one trillion times more energetic than visible light. Although these particles of light, known as photons, are the same as the photons that make up visible light, they behave quite differently simply because they are much more energetic. Viewing the heavens in high-energy photons creates quite a different picture from what we see when we look up at the night sky. There are fewer objects, and they are much more extreme—in the visible, we detect mostly thermal processes and blackbody radiation.

When we view the universe in TeV gamma rays (1 TeV is one trillion electron volts; normal light has a few electron volts of energy), we detect non-thermal radiation and particle acceleration. The light sources that we detect contain super-massive black holes and neutron stars. Some of these sources are highly variable, flaring on a timescale of minutes to days. Until the advent of the Milagro Observatory, located at the LANL Fenton Hill site, there was no instrument capable of continuously monitoring the entire overhead sky in the TeV-energy regime. The existing instruments, known as air Cerenkov telescopes (ACTs), had to be pointed at small regions of the sky (usually at known sources) and could only look at a light source during the time of year that it is overhead at night. Even then, they could only look at the source if the weather was good and the moon was set. But Milagro is ideally suited to monitor the variable TeV universe and discover new sources of TeV gamma rays. With this instrument, we hope to discover new sources of TeV photons, to observe TeV emission from gamma-ray bursts, and to discover primordial black holes or some completely new phenomena.

Physics with Milagro

High-energy gamma-ray astronomy seeks to understand the most extreme environments in the universe and to use the beams of gamma rays from these distant sources to further our understanding of the fundamental laws of physics at energies not attainable in earth-bound experiments. The known sources of gamma rays include supernova remnants, super-massive black holes (known as active galactic nuclei, or AGN), and gamma-ray bursts (the most energetic phenomena in the universe). Gamma rays are also produced when high-energy cosmic rays interact with matter in our galaxy. Other potential sources include more exotic objects (which may or may not be detectable) such as "evaporating" primordial black holes, topological defects, and dark-matter particle annihilation and decay. The gamma rays from distant sources interact with the ambient fields in the universe as they travel to earth. By measuring the effects of these interactions, we can understand the nature of the fields that pervade the universe. Two particle-interaction effects are of concern to us—particle interactions with the intergalactic-infrared-radiation fields and those with the quantum fields that define the universe. The infrared-radiation field results from the formation of, and the nuclear-burning process in, stars and from the subsequent absorption and re-radiation of the energy produced in this process

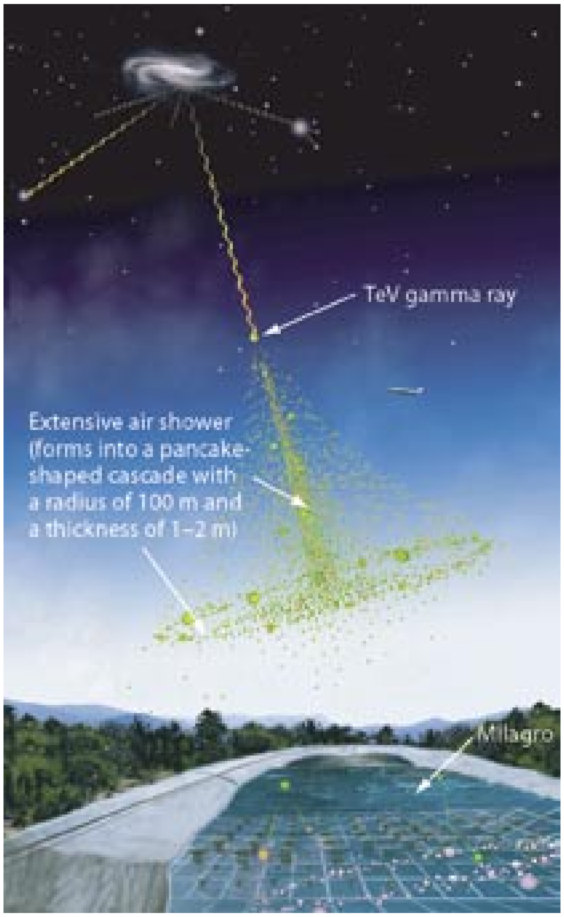

Figure 1. Rendering of Milagro. An astrophysical source emits TeV gamma rays, which propagate to earth. The gamma ray interacts in the atmosphere to generate an EAS. The EAS is composed mostly of electrons, positrons, and gamma rays. The electrons and the positrons emit Cerenkov light as they traverse the water in Milagro. (Cerenkov light is emitted by a charged particle traveling faster than the speed of light in a medium and is similar to a sonic boom.) The gamma rays in the EAS convert to electrons and positrons, which then emit Cerenkov light. The resultant Cerenkov light is detected by the PMTs in the pool of water (see Figure 2). The green particles represent gamma rays; the red particles represent electrons and positrons. (Rendering courtesy of Aurore Simonnet, Scientific Illustrator, Sonoma State University, aurore@universe.sonoma.edu.)

by dust. The field can be determined by measuring the energy- and redshift-dependent absorption of TeV radiation from AGN. Direct measurements are difficult (and so far unsuccessful) because of the large and uncertain foreground fields within our galaxy. The effect of the quantum fields of the universe may be manifest as a violation of Lorentz invariance—an energy dependence of the velocity of light.[1] This effect can be observed (or limited) by measuring the time delay between photons of different energies arriving from across the universe. Bursts of gamma rays provide an excellent source for observing this effect.[2]

Figure 2. A view inside Milagro. The top layer of PMTs is located at the crossing of the grid, and the bottom layer of PMTs is halfway between the grid crossing points. In the photograph, the cover is inflated for installation.

The Milagro Observatory

A cosmic ray or gamma ray entering the earth's atmosphere interacts with atoms and nuclei and loses energy in the process. At high energies, the dominant energy-loss mechanisms are the creation of particles through nuclear interactions in the case of cosmic rays and electromagnetic interactions in the case of gamma rays. The result is a cascade of particles, or EAS. As the cascade propagates through the atmosphere, particles continue to be created until the energy per particle drops below the critical energy of 80 MeV. At this point, the energy loss of the particles becomes dominated by non-particle-creating mechanisms and the EAS begins to die. When the cascade reaches the ground, it has the shape of a rough pancake with a radius of 100 m and a thickness of 1–2 m (Figure 1). A particle cascade initiated by a gamma ray comprises electrons, positrons, and lower-energy gamma rays. A particle cascade initiated by a cosmic ray will also contain muons and some hadrons in addition to the electrons, positrons, and gamma rays.

The Milagro Observatory has 723 PMTs submerged in a six-million-gallon water reservoir. The detector is located at an altitude of 2,630 m above sea level (750 g/cm^2 atmospheric overburden). The reservoir measures 80 m × 60 m × 8 m (depth) and is covered by a light-tight barrier. Each PMT is secured by a Kevlar string to a grid of sand-filled PVC (polyvinyl chloride) pipes sitting on the bottom of the reservoir. The PMTs are arranged in two layers, each on a 2.8-m × 2.8-m grid (Figure 2). The top layer of 450 PMTs (which is under 1.4 m of water) is used primarily to reconstruct the direction of the air shower. By measuring the relative arrival time of the air shower across the array, we can reconstruct the direction of the primary cosmic ray with an accuracy of roughly 0.75°. The bottom layer of 273 PMTs (which is under 6 m of water) is used primarily to discriminate between gamma-ray-initiated air showers and hadronic air showers.

Milagro Results

Background rejection. Because hadronic cosmic rays (mainly protons) are charged, they are deflected by the magnetic fields that pervade our galaxy. Outnumbering the gamma rays by ~ 10,000 to one, they form an isotropic background over which any signal must be detected. The bottom layer of PMTs in Milagro is under a sufficient amount of water such that only the penetrating component of an EAS (muons and showering hadrons) can reach it. Because a gamma-ray-induced EAS is almost completely electromagnetic and a cosmic-ray-induced EAS contains a penetrating component of muons and showering hadrons, Miagro's ability to detect the penetrating component allows us to reject the cosmic-ray background and therefore increases our sensitivity to gamma rays. Figure 3 shows the pattern of light in the bottom layer from three gamma-ray-induced events and three proton-induced events (from Monte Carlo simulations). The proton-induced events contain small bright clumps of light, whereas the gamma-ray-induced events have a relatively uniform, low level of illumination. We have developed a *compactness* parameter that is sensitive to this difference. Using the compactness of the events, we can reject roughly 90% of the cosmic-ray background while retaining 50% of the gamma-ray-induced events.

Observation of the Crab Nebula. The Crab Nebula was the famous supernova observed by Chinese astronomers in 1066. Since that time, it has been detected in every wavelength of astronomy, from the radio to TeV gamma rays. It was the first source to be detected in TeV gamma rays,[3] and it serves as a standard candle for the field of TeV astrophysics. It was critical for Milagro to detect the Crab Nebula and to prove the efficacy of the water Cerenkov technique and our ability to reject the cosmic-ray background. This is the first detection of any source of TeV gamma rays with an EAS array.[4] The flux that we measured from the Crab Nebula is in agreement with the previous measurements by ACTs.

TeV map of the northern hemisphere. Using the same compactness parameter that we used in the Crab Nebula study, we searched for sources of TeV gamma rays from the entire northern hemisphere. Figure 4 shows the most sensitive map to date of the entire northern hemisphere in TeV gamma rays (previous maps have only been made by Milagro and its prototype Milagrito). Notice that in addition to the Crab Nebula there is another bright region in the sky, which corresponds to the active galaxy Markarian 421. Markarian 421 consists of a super-massive black hole with a jet of relativistic particles directed at earth. This black hole has experienced several flaring episodes (in the x-ray band) during our period of observation, and the TeV emission associated with these episodes is correlated with the x-ray emission. This correlation is consistent with leptonic models of gamma-ray production. In these models, electrons are accelerated at shocks that propagate down the jet of relativistic particles that is emitted along the rotation axis; these electrons radiate synchrotron radiation as they bend in the magnetic fields present in the jet. This synchrotron radiation is responsible for the observed x-ray emission. The TeV gamma rays arise from inverse Compton reactions between the primary electrons and the synchrotron photons. Aside from the Crab Nebula and the Markarian 421 black hole, no other object in the northern hemisphere appears as bright as the Crab Nebula (or the Markarian 421) in TeV gamma rays.

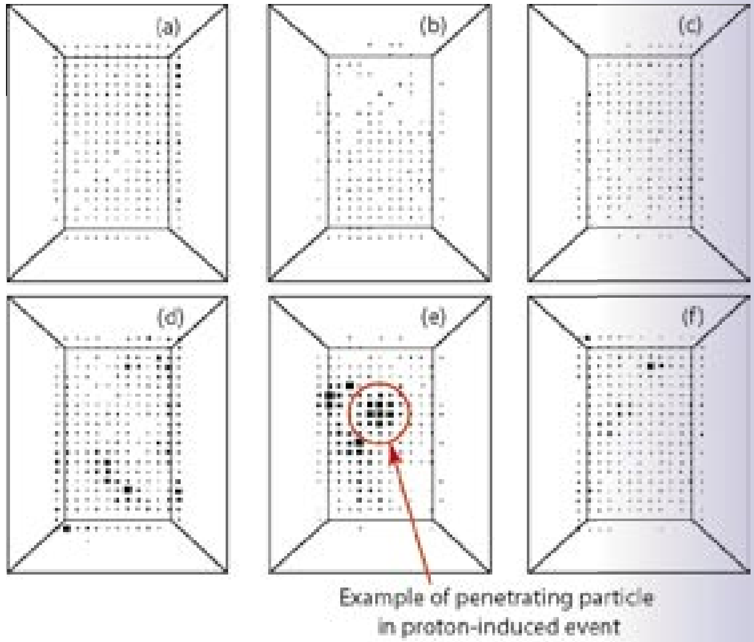

Figure 3. Monte Carlo simulations of the response of the bottom layer of detectors to EASs. The area of each square is proportional to the light level detected in a PMT. The top three events (a, b, and c) are gamma-ray induced events, and the bottom three events (d, e, and f) are proton-induced events. Clear clumps of light are observed in the proton-induced events.

Galactic-diffuse gamma rays. The origin of cosmic rays is still a matter of debate—nearly a century after their discovery! One of the clues to their origin is the energy spectrum of the gamma rays produced by the interactions of the cosmic rays with the matter in our galaxy. The highest-energy measurement of these *galactic-diffuse* gamma rays obtained to date was made by the EGRET instrument onboard the Compton Gamma Ray Observatory.[5] These measurements extend up to ~ 30 GeV and indicate an excess over predictions above several hundred MeV. The measurement of the TeV flux of the galactic-diffuse gamma rays has proven impossible to date. However, this past year Milagro has, for the first time, presented evidence of the existence of a TeV flux of gamma rays arising from interactions of cosmic rays and matter within our galaxy. Milagro has detected a signal based on the analysis of a two-year data run with a significance of 2.8 standard deviations. With another two-year run cycle on Milagro, we will be able to make a conclusive measurement of the TeV flux of galactic-diffuse gamma rays in the galaxy.

Large-scale cosmic-ray anisotropy. We generally assume that the arrival directions of cosmic rays on earth are isotropic. Milagro is the first detector that can make a high-statistics two-dimensional map of the comic-ray arrival directions. With our current data set, we can detect anisotropies as small as one part in 100,000. Figure 5 shows a two-dimensional map of the northern hemisphere in cosmic rays. This figure is similar to Figure 4, except that we have not applied our background rejection cut to the data (which increases our statistics by an order of magnitude). Moreover, we have binned the sky

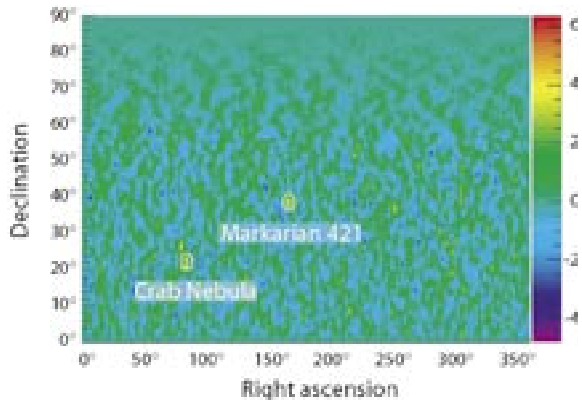

Figure 4. The northern hemisphere as seen in TeV gamma rays. Milagro is the only experiment capable of making such a plot. The two bright regions (circled and marked) are the Crab Nebula and the active galaxy, Markarian 421. The color coding corresponds to the significance of the observed excesses or deficits expressed as standard deviations.

in coarser bins to more clearly show the large-scale structure. A large-scale anisotropy is evident in this data. The red and black regions are areas with an excess of cosmic rays, and the blue regions are areas with a deficit of cosmic rays. The size of the effect is quite small (~ one part in 10,000). The origin of this anisotropy—which is currently under study—may be caused by effects of the solar magnetic field, or it may be imprinted by cosmic-ray production and propagation effects within our galaxy.

Conclusion

Milagro is the first detector of its kind—a large, water Cerenkov EAS detector. Our observations discussed above proved that the technique is sensitive to astrophysical sources of TeV gamma rays and can make measurements that no other current instrument can. Milagro will continue to operate over the next three to five years while we investigate methods to improve the instrument's sensitivity and to explore possible future detectors of a similar design. With the launch of the SWIFT satellite[6] (i.e., a detector that is sensitive to the gamma-ray, x-ray, and optical emissions from gamma-ray bursts) in 2004, Milagro's *all-sky* and *all-time* capabilities will be more important than ever before. As the only instrument capable of measuring the prompt TeV component of gamma-ray bursts, Milagro is poised to make enormous contributions to our understanding of gamma-ray bursts and perhaps of quantum gravity.

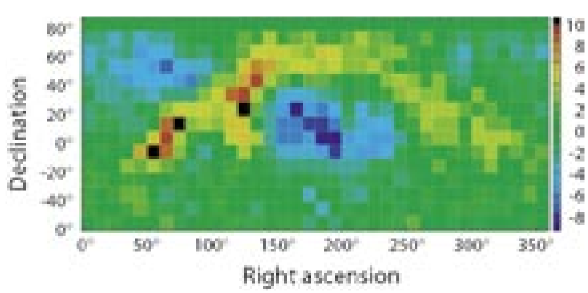

Figure 5. The northern sky as seen in TeV cosmic rays. The red to black areas represent directions from which there is an excess (over uniform) of cosmic rays, and blue regions are directions from which there is a deficit of cosmic rays.

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6. See http://swift.gsfc.nasa.gov/.

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